A \( L_1 \) Adaptive Control Scheme for UAV Carrier Landing Using Nonlinear Dynamic Inversion

Ke Lu\(^1,2\) and Chunsheng Liu\(^1\)

\(^1\)College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu 210016, China
\(^2\)Science & Technology on Rotorcraft Aeromechanics Laboratory, China Helicopter Research and Development Institute, Jingdezhen, Jiangxi, 333001, China

Correspondence should be addressed to Ke Lu; looknuaa@163.com

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This paper presents a \( L_1 \) adaptive controller augmenting a dynamic inversion controller for UAV (unmanned aerial vehicle) carrier landing. A three axis and a power compensator NDI (nonlinear dynamic inversion) controller serves as the baseline controller for this architecture. The inner-loop command inputs are roll-rate, pitch-rate, yaw-rate, and thrust commands. The outer-loop command inputs come from the guidance law to correct the glide slope. However, imperfect model inversion and nonaccurate aerodynamic data may cause degradation of performance and may lead to the failure of the carrier landing. The \( L_1 \) adaptive controller is designed as augmentation controller to account for matched and unmatched system uncertainties. The performance of the controller is examined through a Monte Carlo simulation which shows the effectiveness of the developed \( L_1 \) adaptive control scheme based on nonlinear dynamic inversion.

1. Introduction

Aircraft carrier landings have been regarded as one of the most challenging phases of flight due to the extremely tight space available for touchdown on the flight deck of an aircraft carrier. The pilot must aim for a single spot on the flight deck with a very small margin for error [1]. The area used to land on the deck is very small, which is only about 55 feet wide and 40 feet long. A small deviation from the desired landing box may lead to crashing into other aircraft on the flight deck. The problem of autonomous carrier landing of UAV is highly challenging due to wind gust disturbances and ship motion under high sea states [2]. However, carrier flight operations are necessary for the support of combat operations and must take place whenever they are needed. With consideration of all of the effects, developing a system which automates the carrier landing process is extremely important and will increase the design difficulty of controller [3].

While the topic of automated carrier landing has been studied for several decades, most researchers have focused on linear control methods. H-dot and glide-slope feedback are used as their bases which are found in Ref. [4–6]. However, with air turbulence added, the landing performances of these controllers were degraded [5]. As carrier landing systems are inherently nonlinear, nonlinear control schemes should be the next logical step with the development of computer capability. In Ref. [7], Steinberg expanded his investigation to the application of a fuzzy logic carrier landing system. What he cared about was the ability of the controller to adapt to changing conditions, and the initial results were promising. In Ref. [8], Steinberg and Page compared the baseline performances of several different nonlinear control schemes applied to automated carrier landing. It showed that the nonlinear control may be a very good choice for future carrier landing system. In Ref. [9], a fuzzy-logic-based approach was used to design an autonomous landing system for unmanned aerial vehicles. In Ref. [10], preview control for unmanned aerial vehicle carrier landing was presented. In Ref. [11], active disturbance rejection control was used for unmanned aerial vehicle carrier landing. These nonlinear control methods proved useful in this application. Denison applied nonlinear dynamic inversion to design a carrier
landing system for unmanned combat aerial vehicles considering turbulence [12]. The performance of the system was evaluated using Monte-Carlo simulations. However, after adding wind and sea state turbulence, the controller performance was degraded. Although nonlinear dynamic inversion could eliminate the need for extensive gain scheduling, however, since the system parameters are not exactly known and the plant inversion is not accurate, dynamic inversion controller may possess performance degradation. In order to solve this problem, in Ref. [13], online neural networks were used to compensate plant inversion error. Sliding mode variable structure control could be used to enhance the system robustness, but the chatter problem is not very acceptable [14]. Another widely used method is the linear robust controller [15, 16]. However, a high-order robust controller is required, such as a fourteen-order controller to ensure the flying control system robustness for X-38 [17].

$L_1$ adaptive control algorithm is a recently developed adaptive control methodology. The key feature of $L_1$ adaptive control architecture is its fast and robust adaptation, which does not interact with the trade-off between performance and robustness [18]. It was developed with aerospace control in mind and has been found to be suitable for flying applications [19, 20].

In this paper, nonlinear dynamic inversion based controller is designed for carrier landing flight control system. Then $L_1$ adaptive control algorithm is used to augment the baseline controller. The effects of the adaptive element on the flight control system are demonstrated with Monte Carlo simulations.

2. UAV Flight Dynamics Model and Carrier Landing Environment

In this section, a nonlinear UAV flight dynamics model is developed. Then, the carrier landing environment is described.

2.1. UAV Flight Dynamics Model. The aircraft which was used for this study was the Joint Unmanned Combat Air System (J-UCAS) Equivalent Model (EQ model) developed by the Air Force Research Laboratory (AFRL) [21]. The EQ model has three sets of control surfaces: flaps for pitch control, elevons for roll control, and clamshells for yaw control. The physical parameters for the aircraft are summarized in Table 1.

The simulation uses the standard equations of motion and kinematic relations found in a variety of standard references on flight dynamics.

\[
\dot{X} = F(X, U, \sigma),
\]

where $F(.) \in \mathbb{R}^{12 \times 1}$ denotes a vector of nonlinear algebraic equations involving $X$, $U$, and $\sigma$. The state variables are given in the form of a vector $X \in \mathbb{R}^{12 \times 1}$: $U = [\delta_e, \delta_i, \delta_r, \delta_y]$ denotes a vector constituting the control inputs; $\sigma$ is unmodeled nonlinearity dynamics.

2.2. Aircraft Carrier Model and Wind Turbulence Model. The Nimitz-class carrier is employed in this paper. There are 4 wires spaced 40 feet apart for aircraft landing. The detailed parameters can be found in Ref. [12]. The aircraft carrier motion is composed of a forward motion with constant velocity and perturbations caused by sea states. The perturbations are composed of rotational degrees and translational degrees of freedom. The rotational degrees of freedom are termed roll and pitch. In the translational degrees of freedom, up and down motion is called heave, forward to aft motion is called surge, and port to starboard motion is called sway [12]. The perturbations are modeled as sinusoidal waves using the information provided in Table 2 [12, 22]. Sea state 0 refers to calm seas and the values are all zero, and sea state 6 is extremely heavy seas.

A large source of touchdown error is the turbulent air environment found in the approach path [4]. The wind turbulence model is composed of the free atmospheric turbulence and ship burble. The burble is the wind pattern found immediately behind the carrier fantail, which consists of a steady component, an unsteady component, and a periodic component [22].
The wind turbulence model is given by

\[
\begin{align*}
U_g &= U_1 + U_2 + U_3 + U_4, \\
V_g &= V_1 + V_4, \\
W_g &= W_1 + W_2 + W_3 + W_4,
\end{align*}
\]  

where \(U_1, V_1,\) and \(W_1\) represent free atmospheric turbulence; \(U_2\) and \(W_2\) represent the steady component of burble turbulence; \(U_3\) and \(W_3\) represent the periodic component of burble turbulence; \(U_4, V_4,\) and \(W_4\) represent random component of burble turbulence. The periodic component could be ignored, as it is due to the slow pitch periodic motion of carrier. The random component of burble and free atmospheric turbulence are modeled using Dryden turbulence [12]. In this study, the Dryden wind turbulence model uses the Dryden spectral representation by passing band-limited white noise through appropriate forming filters to meet the MIL-HDBK-1797B, while the steady component is essentially a shift in all components of the turbulence, which causes a 6 ft drop below the glide slope and consequent touchdown 125 ft short of the ideal touchdown point [4].

3. The Controller Design

In this section, a \(L_1\) adaptive augmented dynamic inversion controller for UAV carrier landing is designed. In this study, the command inputs for the controller are provided by the guidance system. The guidance system generate the yaw angle and pitch angle commands which can be found in Ref. [12]. The side-slip angle command is always zero, and the angle of attack command depends on Approach Power Compensation System. The Approach Power Compensation System automatically controls thrust to maintain a reference angle of attack during the carrier approach, thus effectively controlling the flight path angle through pitch angle [5, 23]. The baseline controller is a full nonlinear dynamic inversion controller based on large part of Ref. [24] and Ref. [12]. An inner-loop controller, designed by dynamic inversion, is used to linearize the UAV dynamics. This inner-loop controller lacks guaranteed robustness to uncertainties in the flight dynamics model. This would cause degradation of NDI controller performance and even lead to the failure of the carrier landing. To address robustness to model uncertainties, a \(L_1\) adaptive controller is designed as augmentation controller. The complete architecture is presented in Figure 1.
3.1. Baseline Controller: Nonlinear Dynamic Inversion. Nonlinear dynamic inversion is a technique in which feedback is used to linearize the system to be controlled and to provide desired dynamic [15, 24]. The inner loop controller is used to control the angular accelerations and thrust of the aircraft. Thus, a simple first-order equation was added for thrust control [12].

\[ T = \frac{1}{r} (\delta, T_{\text{max}} - T), \]

where \( r \) is the engine time constant and \( T_{\text{max}} \) is the maximum at the given flight condition.

The inner-loop dynamics are presented below:

\[ \dot{X}_\text{in} = F_\text{in}(X)X_\text{in} + G_\text{in}(X)U_\text{in}, \]

where \( X_\text{in} = [p, q, r] \); \( F_\text{in}(.) \) \( \in \mathbb{R}^{4 \times 1} \) and \( G_\text{in}(.) \) \( \in \mathbb{R}^{4 \times 1} \) are vectors of nonlinear algebraic equations.

With the pseudocontrol signal \( X_\text{out} \), the general nonlinear dynamic inversion control law is given by

\[ U_\text{in} = \tilde{G}_\text{out}^{-1}(X_\text{ind} - F_\text{in}(X)X_\text{in}), \]

where the over-hats have been used to denote that parameters are estimated, which are provided through look-up tables in a real-time operation.

Inserting equation (5) into equation (4) leads to the following equation:

\[ \dot{X}_\text{in} = F_\text{in}(X)X_\text{in} - G_\text{in}(X)\tilde{G}_\text{in}^{-1}(X)F_\text{in}(X)X_\text{in} + G_\text{in}(X)\tilde{G}_\text{in}^{-1}X_\text{ind}. \]

Equation (6) is the actual closed-loop input/output relation after applying feedback linearization. Moreover, if the estimates in equation (6) are exact, then equation (6) yields an exact linear relation:

\[ \dot{X}_\text{in} = X_\text{ind}. \]

The out-loop dynamics inversion controller is designed in much the same way as the interloop controller. The out-loop dynamics are presented below:

\[ X_\text{out} = F_\text{out}(X_\text{out}) + G_\text{out}(X_\text{out})X_\text{in}, \]

where \( X_\text{out} = [\theta, \psi, \beta, \alpha]^T \); \( F_\text{out}(.) \) \( \in \mathbb{R}^{4 \times 1} \) and \( G_\text{out}(.) \) \( \in \mathbb{R}^{4 \times 1} \) are vectors of nonlinear algebraic equations.

With the pseudocontrol signal \( X_\text{out} \), the general nonlinear dynamic inversion control law is given by

\[ X_\text{ind} = \tilde{G}_\text{out}^{-1}(X_\text{out} - F_\text{out}(X_\text{out})). \]

Inserting equation (9) into equation (8) leads to the following equation:

\[ X_\text{out} = F_\text{out}(X_\text{out}) + G_\text{out}(X_\text{out})\tilde{G}_\text{out}^{-1}(X_\text{out} - F_\text{out}(X_\text{out})). \]

If the estimates in equation (10) are exact, then equation (10) yields an exact linear relation:

\[ X_\text{out} = X_\text{outd}. \]

3.2. L1 Adaptive Controller. The NDI-based controller assumes exact knowledge of the system. However, this is not the case. To address robustness to model uncertainties, a \( L_1 \) adaptive controller is designed as augmentation controller to compensate for unmodeled dynamics.

The pitch channel under baseline controller can be written in the form of

\[ \dot{x}_q = -A_m x_q + B_m u_q(t) + f(t, x_q(t), z(t)), \]
\[ x_q(0) = x_{q0}, \]
\[ \dot{x}_z(t) = g(t, x_z(t), q), \]
\[ x_z(0) = x_{z0}, \]
\[ z(t) = g_0(t, x_z(t)), \]
\[ y(t) = c^T x_q(t), \]

where \( x_q = [\theta, q]^T \); \( A_m \in \mathbb{R}^{2 \times 2} \) is a known real number defining the desired dynamics for the closed-loop system; \( B_m \), \( c \) are known constant vectors; \( f(t, x_q(t), z(t)) \) represents all nonlinearities and further uncertainties of the system. The unmodeled dynamics of the states \( Z \) contribute to these uncertainties; \( y(t) \) is the system output.

The system (12) can be written in the form

\[ \dot{x}_q = -A_m x_q + B_m (u_q(t) + f_1(t, x_q(t), z(t))) + B_{um} f_2(t, x_q(t), z(t)), \]
\[ x_q(0) = x_{q0}, \]
\[ \dot{x}_z(t) = g(t, x_z(t)), \]
\[ x_z(0) = x_{z0}, \]
\[ z(t) = g_0(t, x_z(t)), \]
\[ y(t) = c^T x_q(t), \]
where $B_{um}$ is created as the null space of $B_m^T$ while keeping the square matrix $[B_m \ B_{um}]$ of full rank. $f_1(\cdot)$ represents the matched component of the uncertainties, whereas $B_{um}f_2(\cdot)$ represents the unmatched component.

The system above verifies the following assumptions [25].

**Assumption 1** (Boundedness of $f_1(t, 0)$). There exists $B_i > 0$, such that $\|f_i(t, 0)\|_{\infty} \leq B_i$ holds for $t \geq 0$ and for $i = 1, 2$.

**Assumption 2** (Semiglobal Lipschitz condition). For arbitrary $\delta > 0$, there exist positive $K_{d\delta}, K_{2\delta}$, such that

$$\|f_i(t, x_1) - f_i(t, x_2)\|_{\infty} \leq K_{d\delta}\|x_1 - x_2\|_{\infty}, \quad i = 1, 2, \quad (14)$$

for all $\|x_j\|_{\infty} \leq \delta, j = 1, 2$, uniformly in $t$.

**Assumption 3** (Stability of unmodeled dynamics). The $x_r$-dynamics are BIBO stable with respect to both initial conditions $x_{q0}$ and input $x(t)$.

In this study, the uncertainties are mainly caused by aerodynamic parameters and the wind disturbance. They are always uniformly bounded and limited in how fast they can change. Thus, these assumptions are reasonable.

### 3.2.1. Piecewise Constant $L_1$ Adaptive Controller Design

The structure of the $L_1$ adaptive augmentation is depicted in Figure 2. In this application a piecewise constant type of $L_1$ adaptive controller is composed of a state predictor, an adaptive law, and a control law.

1. **State predictor**

$$\dot{x}_q = A_m\hat{x}_q(t) + B_m(u(t) + \hat{\sigma}_1(t)) + B_{um}\hat{\sigma}_2(t) \quad (15)$$

2. **Adaptive law**

$$\begin{bmatrix} \hat{\sigma}_1(t) \\ \hat{\sigma}_2(t) \end{bmatrix} = -B^{-1}\Phi^{-1}(T_s)e^{A_m T_s}(\hat{x}_q(iT_s) - x_q(iT_s)), \quad (16)$$

where $B = [B_m \ B_{um}]$, $\Phi(T_s) = A_m^i e^{A_m T_s} - I$, and $T_s$ is adaptation sampling time.

3. **Control law**

$$u_{ref}(s) = C(s)\left[k_g r(s) - \hat{\sigma}_1(s) - H_m(s)H_{um}(s)\hat{\sigma}_2(s)\right], \quad (17)$$

where $H_m(s) = c^T(sI - A_m)^{-1}B_m$, $H_{um}(s) = c^T(sI - A_m)^{-1}B_{um}$, and $C(s)$ is low-pass filter with $C(0) = 1$

### 3.2.2. Closed-Loop Reference System and Performance Bounds

We define the closed-loop reference system as [25]

$$\begin{align*}
\dot{x}_{qref} &= -A_m x_{qref} + B_m(u_{qref}(t) + f_1(t, x_{qref}(t), z(t))) + B_{um} f_2(t, x_{qref}(t), z(t)), \\
x_{qref}(0) &= x_{q0}, \\
u_{qref} &= -C(s)\left[\eta_{1ref}(s) + H_m(s)H_{um}(s)\eta_{2ref}(s) - k_g r(s)\right] \\
y_{ref}(t) &= c^T x_{qref}(t),
\end{align*} \quad (18)$$

where $\eta_{1ref}(s)$ and $\eta_{2ref}(s)$ are the Laplace transforms of the signals $\eta_{1ref}(t) = f_1(t, x_{qref}(t), z(t)), \ i = 1, 2$.

**Theorem 1** [25]. Given the adaptive closed-loop system with the $L_1$ adaptive controller defined via (15), (16), and (17), subject to the $L_1$-norm condition, the controlled system (13) will follow the reference system within the following limits:

$$\begin{align*}
\|x_q - x_{qref}\|_{s\infty} &\leq y_s(T_s), \\
\|u_q - u_{qref}\|_{s\infty} &\leq y_u(T_s),
\end{align*} \quad (19)$$

where $y_s$ and $y_u$ are dependent on $f_1(t, x)$ bounds and $L_1$ controller design parameters, $A_m$, $C(s)$, and $T_s$.

**Remark 1.** As the sampling period $T_s$ goes to zero, the system (13) will follow the reference system (18) arbitrarily.

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**Figure 3:** Pitch angle capture task without parameter perturbations.
closely. It implies that the performance limitations are consistent with the hardware limitations.

\[
\lim_{t \to 0} y_x = 0, \\
\lim_{t \to 0} y_u = 0, \\
\]

**Remark 2.** the low-pass filter \( C(s) \) defines the trade-off between performance and robustness. Reducing the bandwidth of the filter, the time-delay margin of the system can be increased, while the performance reduced. On the contrary, increasing the bandwidth of the filter leads to improved performance with reduced robustness.

### 3.2.3. Implementation Details

The desired dynamics for pitch channel is set by a parameter \( \omega_\theta = 5 \) rad/s, which corresponds to closed-loop reference response bandwidth. The damping parameter is set to 0.9 in this design.

The low-pass filter guarantees that the control signal stays in the low-frequency range even in the presence of fast adaptation. In Ref. [25], the authors suggest that the bandwidth of the filter is not frequencies beyond the control channel bandwidth through to the control signal. On the other hand, the filter bandwidths are related to the corresponding reference system bandwidth. So the filter bandwidths should be higher than the desired system [26].

As presented before, the sampling time \( T_s \) has a significant influence on the \( L_1 \) adaptive controller with piecewise-constant adaptation law. In Ref. [25], the authors suggest that the sampling time \( T_s \) is to choose as low as possible, considering available computing power [25, 27]. After a series of simulations, the following parameters of the \( L_1 \) controller were obtained:

\[
C(s) = \frac{30}{s + 30}, \quad T_s = 0.005s. \\
\]

### 4. Simulations

In order to examine the performance of \( L_1 \) augmented dynamic inversion controller for UAV carrier landing, three simulation scenarios are considered.

**Scenario 1.** Pitch angle capture simulation.

In this case, aerodynamic parameters are varied by 20%. Mass and mass inertia properties are varied by 5%. The control effectiveness are varied by 50%. Figure 3 shows the pitch angle tracking performance of the dynamic inversion controller with linear compensation versus its performance with \( L_1 \) adaptive controller without parameter perturbations. Without parameter perturbations, performances of both control laws are very similar. However, as the parameter perturbations are added (Figure 4), the performance of the linear controller degrades while the \( L_1 \) controller manages to reduce effects of parameter changes to controlled states better.

**Scenario 2.** UAV carrier landing simple simulation.

In this case, turbulence and sea state effects are not included. The forward speed of UAV is \( V_a = 65 \) m/s, and the aircraft carrier speed is \( V_b = 5 \) m/s. Figure 5 depicts the height change during the carrier landing task. Figure 6 depicts the top-down view of the trajectory of both the UAV and the carrier. When the simulation began, the UAV immediately began to turn to intercept the glide path. As it approached the prescribed glide path, it came out approximately on the glide path at the landing heading with little overshoot. It then maintained the prescribed glide path all the way to touchdown. These results show that the controller performs well when turbulence and sea state effects are not included.

**Scenario 3.** UAV carrier landing Monte Carlo simulation.

In this case, the performance of the controller is evaluated through a Monte Carlo simulation. In order to compare with Ref [12], the same simulation conditions are set. According to Ref. [22], the simulation results of the total wind disturbance components \( U_g, V_g, \) and \( W_g \) are shown in Figure 7, and the deck motion under sea state 4 is shown in Figure 8.
The number of 500 Monte Carlo simulation experiments are carried out. In this case, wind turbulence and sea state effects are included. The landing dispersions under NDI baseline controller with linear compensation can be found in Ref [12], while the landing dispersions with $L_1$ adaptive control augmentation under the same simulation conditions is shown in Figure 9. It can be derived from Ref [12] that the increase in wind turbulence greatly degraded the performance of the controller, as 13 (2.6%) caught the 1 wire, 123 (24.6%) caught the 2 wire, 250 (50.0%) caught the 3 wire, and 114 (22.8%) caught the 4 wire [12]. However, when the $L_1$ adaptive augmentation was added to the control loop, all 500 simulation runs resulted in a successful trap. Of these, 473 (95%) landed in the desired landing area.

5. Conclusions

In this paper, the design of a nonlinear inversion controller for UAV carrier landing has been developed. Furthermore, it has been explained how to augment this baseline controller with a $L_1$ adaptive controller. The nonlinear simulation results demonstrate that the baseline controller performs well when the system model is accurate and without wind turbulence. However, when turbulence and sea state effects are included, the landing dispersion under $L_1$ adaptive augmentation provides significant improvement.

Data Availability

This publication is supported by multiple datasets, which are openly available at locations cited in References.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References


